Generators

Andrzej Siódmok

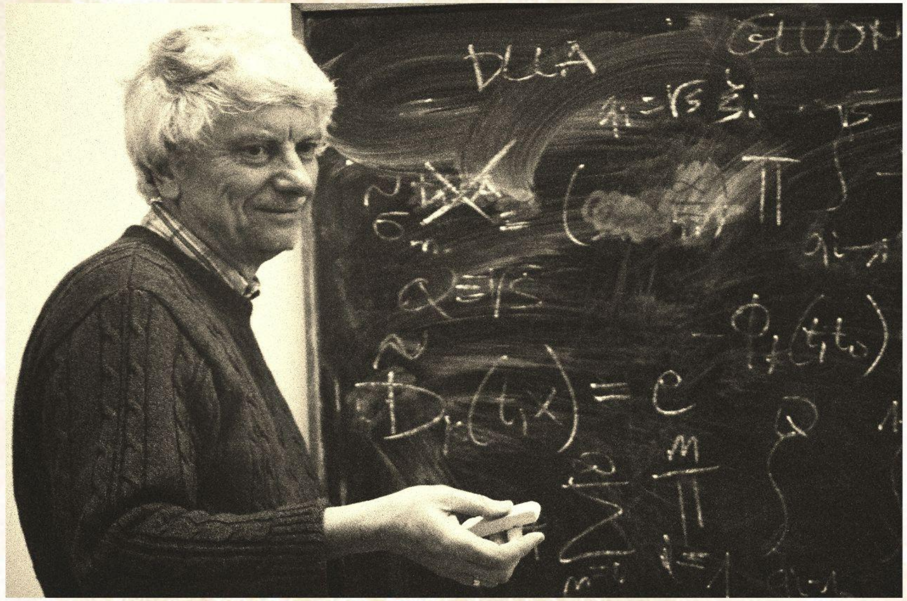
NCN, Poland Grant No. 2019/34/E/ST2/00457

XXX Cracow EPIPHANY Conference

Open scientific and memorial session dedicated to Prof. Stanislaw Jadach

10 January 2024, 14:30-18:30, Auditorium Maximum, ul. Krupnicza 33

Krakow, Poland



We would like to invite everyone to an open scientific and memorial session dedicated to Prof. Stanislaw Jadach, who passed away in 2023

Organizing Committee:

Marcin Chrząszcz	(IFJ PAN)
Iwona Grabowska-Bołd	(AGH)
Marek Jeżabek	(IFJ PAN)
Aleksander Kusina	(IFJ PAN)
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Wiesław Płaczek	(Jagiellonian University)
Sebastian Sapeta	(IFJ PAN)
Magdalena Sławińska	(IFJ PAN)
Andrzej Siódmok	(Jagiellonian University)
Maciej Skrzypek	(IFJ PAN)
Zbigniew Wąs	(IFJ PAN)

Invited Speakers:

Alain Blondel
Rolf-Dieter Heuer
Patrick Janot
Bennie F.L. Ward
Zbigniew Wąs

http://epiphany.ifj.edu.pl

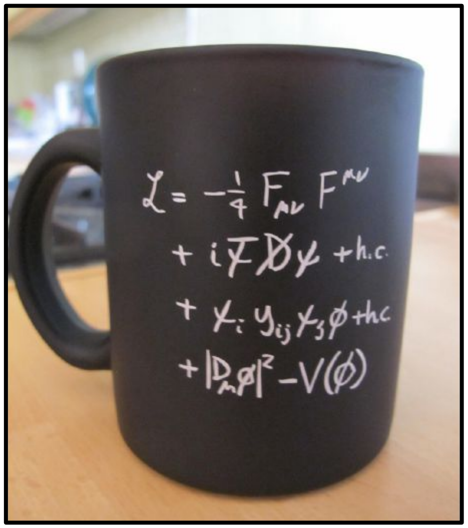
PAN

Standard Model

There is a **huge gap** between a one-line formula of a fundamental theory, like the Lagrangian of the SM, and the experimental reality that it implies

Theory

Standard Model Lagrangian



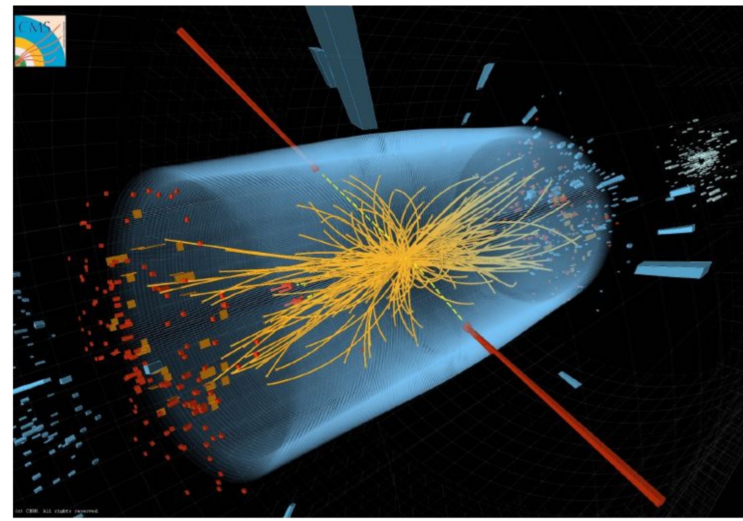
Data makes you smarter

It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong.

Richard P. Feynman

Experiment

LHC event

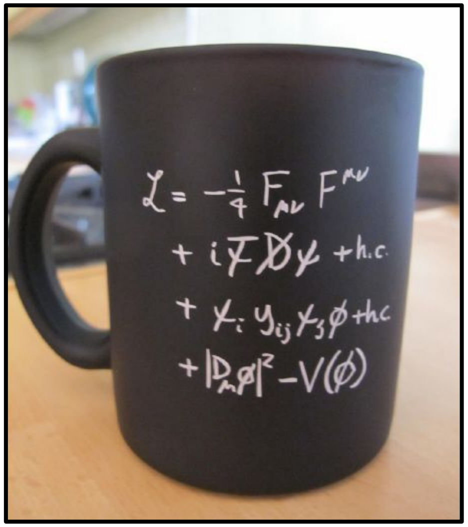


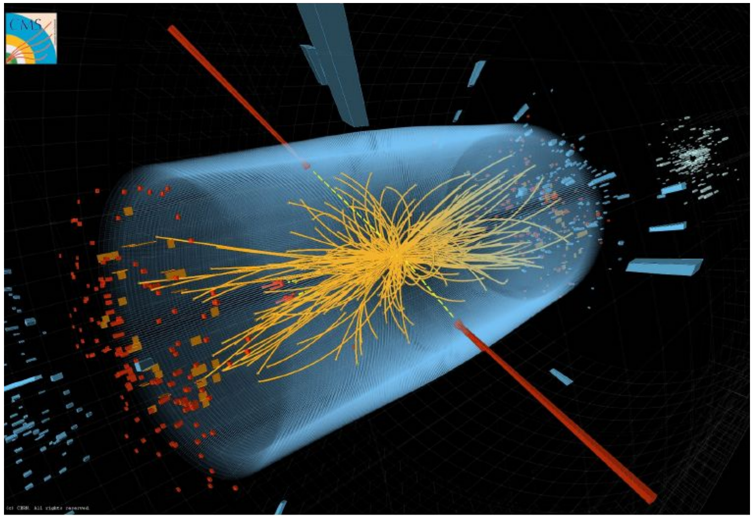
Standard Model

There is a **huge gap** between a one-line formula of a fundamental theory, like the Lagrangian of the SM, and the experimental reality that it implies

Theory — **Standard Model Lagrangian**

Experiment — **LHC event**





- MC event generators are designed to bridge the that **gap**
- “Virtual collider” ⇒ Direct comparison with data

⇩

Almost all **HEP measurements and discoveries** in the modern era have **relied on MCEG**, most notably the discovery of the Higgs boson.

[see Michał Bluj and Martina Javurkova talks]

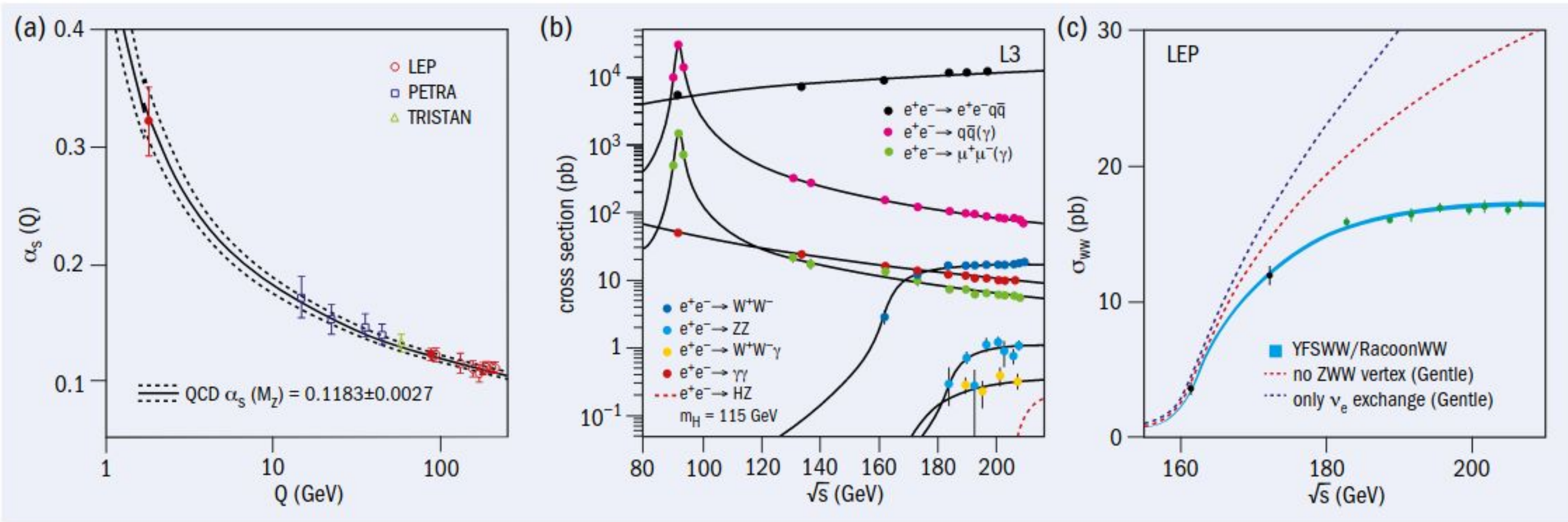
Published papers by ATLAS, CMS, LHCb: **2252**
Citing at least 1 of 3 existing MCEG: **1888** (**84%**)

Outline Generators

1. LEP
2. LHC
3. Future-ee

1. LEP

LEP's electroweak leap, CERNCOURIER



1. LEP legacy MC

Precise process-oriented MC
[main focus on QED/EW]

- BHLUMI (low angle Bhabha), BHWIDE:

$$e^+e^- \to e^+e^-(n\gamma)$$

- KKMC:

$$e^+e^- \to f\bar{f}(n\gamma),\ f = \mu, \tau, q, \tau \to X$$

- KORALW, YFSWW, RacoonWW

$$e^+e^- \to W^+W^-(n\gamma) \to 4f(n\gamma)$$

$$\vdots$$

General purpose MC
[main focus on QCD]

- Herwig 6
- PYTHIA 6/JETSET
  Ariadne

Specialized programs
- PHOTOS - *universal Monte Carlo for QED radiative corrections*
- TAUOLA - *tau decay library*

1. LEP legacy MC

Example:
Precise process-oriented MC

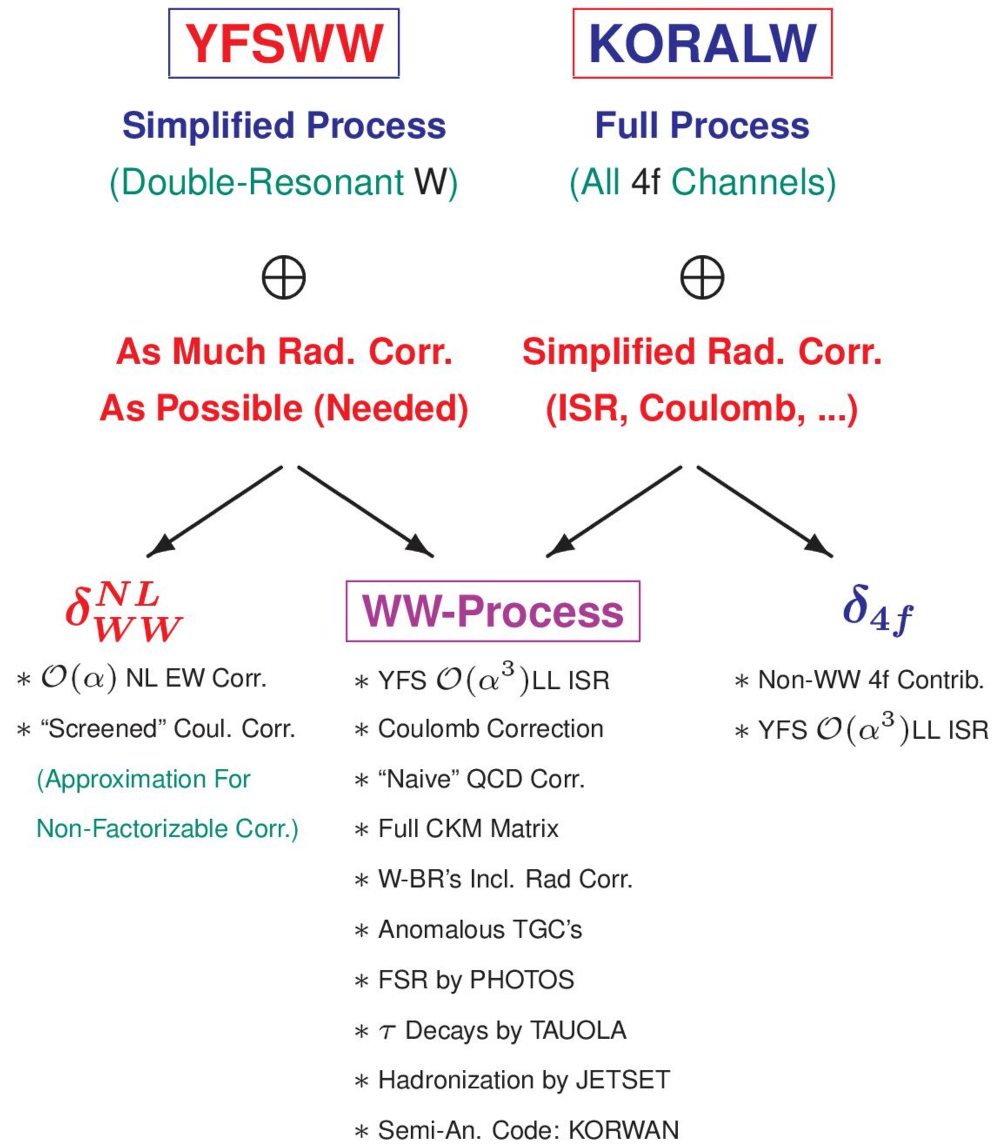
[S. Jadach, W. Placzek, M. Skrzypek, B.F.L. Ward, Z. Was]

$$e^+e^- \to W^+W^-(n\gamma) \to 4f(n\gamma)$$

KORALW, YFSWW

The YFS formalism provides a robust method for resumming the emission of real and virtual photons in the soft limit to all orders. This resummation can be further improved by including exact fixed-order expression in a systematic way.

(see A. Price's talk)



1. LEP legacy MC

Example:
Precise process-oriented MC

[**S. Jadach**, W. Placzek, M. Skrzypek, B.F.L. Ward, Z. Was]

$$e^+e^- \to W^+W^-(n\gamma) \to 4f(n\gamma)$$

KORALW, YFSWW

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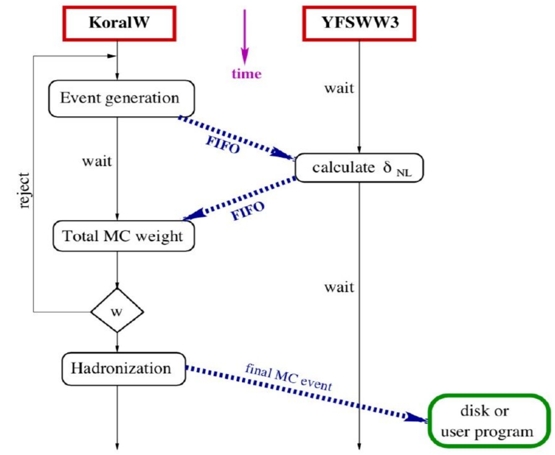
(see A. Price's talk)

YFSWW	KORALW
Simplified Process	**Full Process**
(Double-Resonant W)	(All 4f Channels)

Merge of KoralW and YFSWW3 = KandY

Possible because the underlying photonic distribution is the same YFS-ISR in both codes. All other photonic effects are included as weights. So are the $\mathcal{O}(\alpha)$ EW corrs.

Concurent realization of $\sigma_{K/Y}$ with "named pipes"

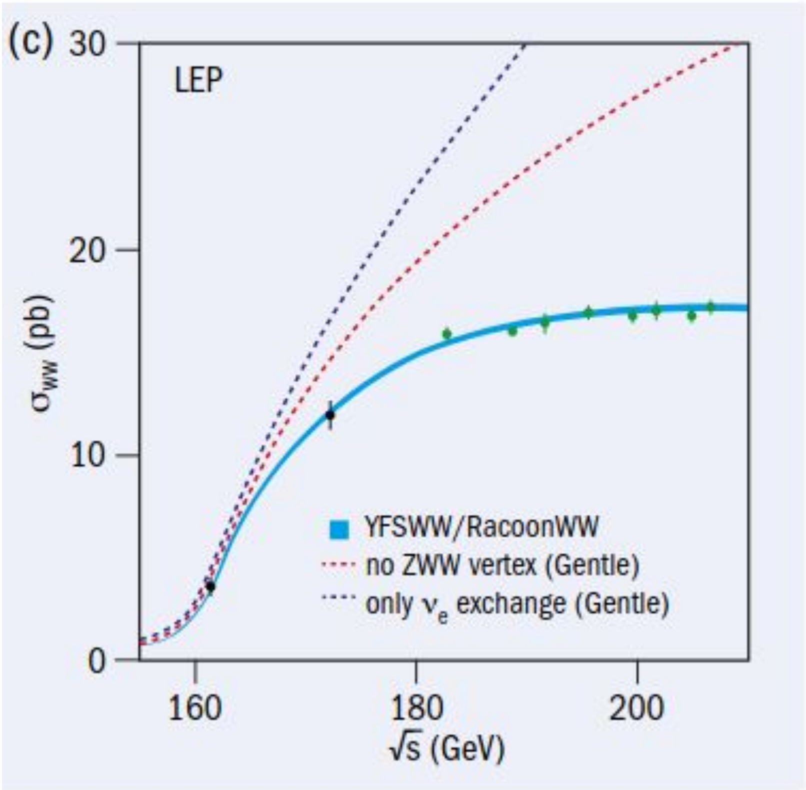


Works effectively as a single MC event generator

1. LEP legacy MC

Example

Process-oriented precision MC



$$e^+e^- \to W^+W^-(n\gamma) \to 4f(n\gamma)$$

YFSWW:
[**Jadach**, S., Płaczek, W., Skrzypek, M., Ward, B., & Wąs, Z., CPC 2001, 140(3)]

RacoonWW:
[Denner, A., Dittmaier, S., Roth, M., & Wackeroth, D. CPC 2003, 153(3)]

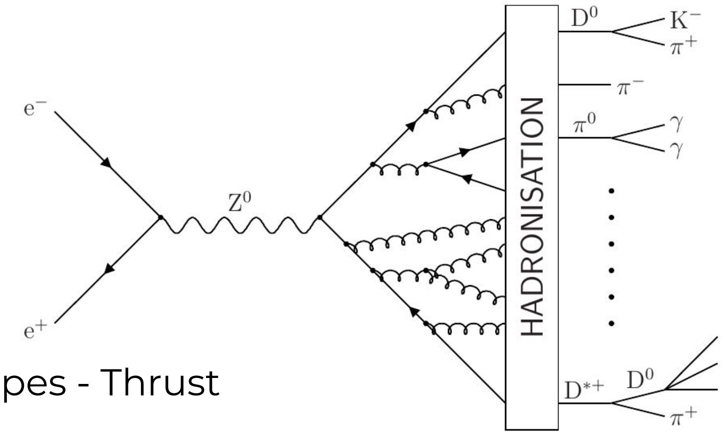
- 0.3% difference due to different treatment of QED: YFS vs Collinear Resummation
- important to have at least 2 independent MC!

The only tools capable to calculate QED+EW Standard Model predictions for the total cross section and distributions of the e+e− → W+W− process. They were also used to extract (fit) the mass of the W boson from data.

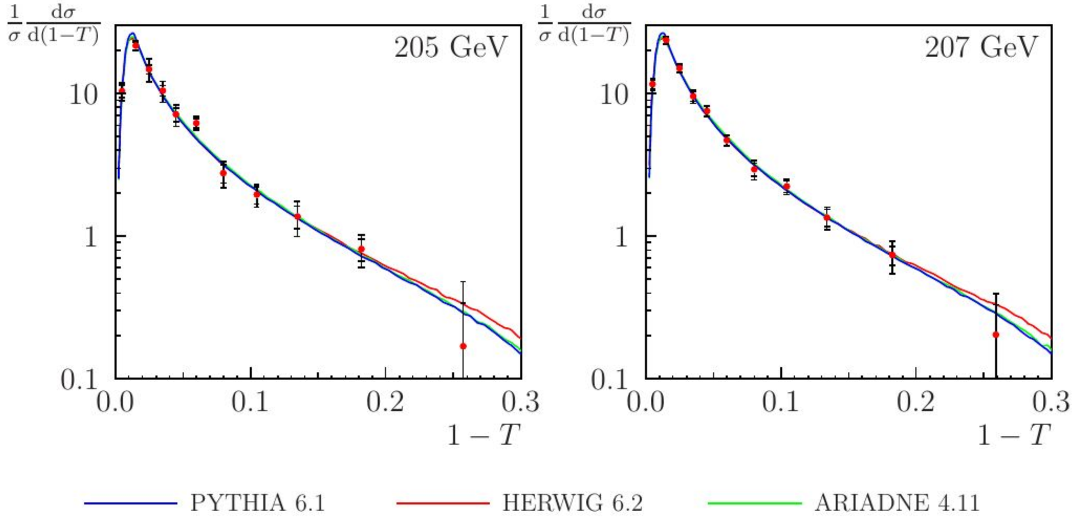
1. LEP legacy MC

Example:
General purpose MC

" The Monte Carlo programs used in our analysis to simulate multihadronic events are $\mathcal{KK}$2f 4.01/4.13 [46], PYTHIA 6.125 [47], HERWIG 6.2 [48] and ARIADNE 4.11 [49]."

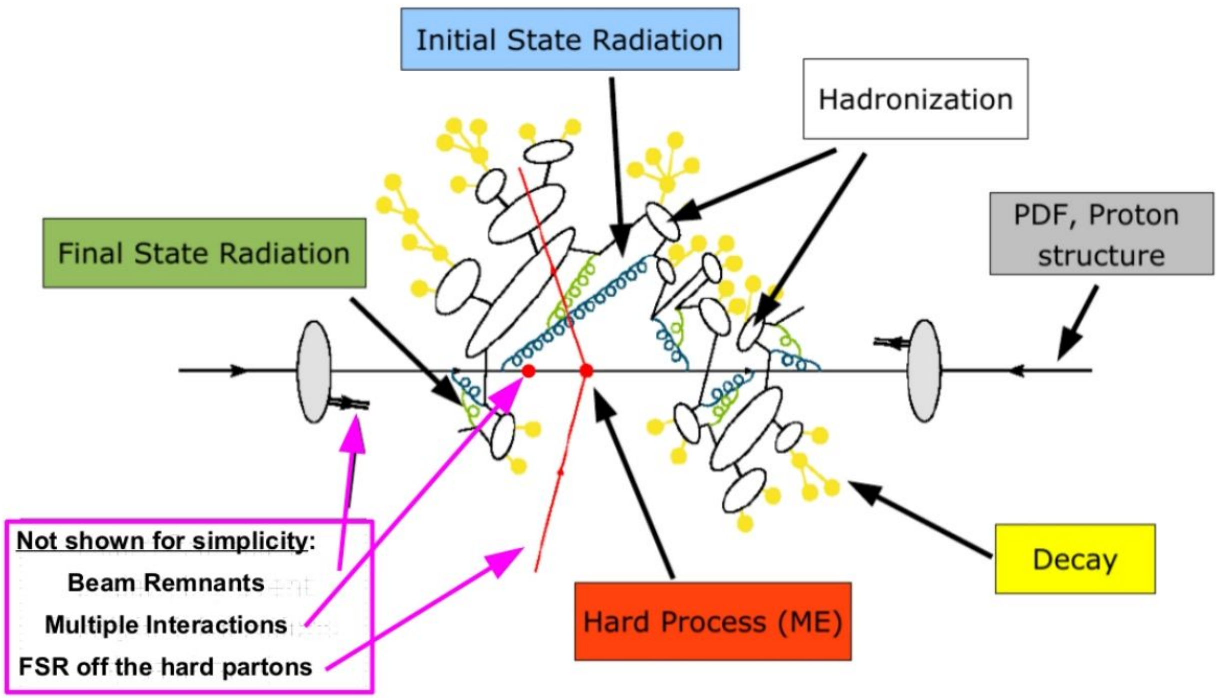


Hadronic Event Shapes - Thrust



LHC: QCD machine

Main progress in General purpose MC



taken from Stefan Gieseke©

The general approach is the same in different programs but the models and approximations used are different.

2. LHC MC

General purpose MC the Workhorses of the LHC:

Herwig 7: Successor to EARWIG (begun in 1984). Originated in coherence studies: angular ordering parton shower. Cluster model. Last version: **Herwig 7.2** [Bellm, Bewick, Ravasio, Gieseke, Grellscheid, Kirchgaesser, Masouminia. Nail, Papaefstathiou, Platzer, Rauch, Reuschle, Richardson, Seymour, **Siodmok**, Webster, *Eur.Phys.J.C* 80 (2020)]

PYTHIA 8: Successor to JETSET (begun in 1978). Originated in hadronization studies: Lund String. Last version: **PYTHIA 8.3** ["A comprehensive guide to the physics and usage of PYTHIA 8.3" 315 pages! Bierlich, C., Chakraborty, S., Desai, N., Gellersen, L., Helenius, I., Ilten, P., Lönnblad, L., Mrenna, S., Prestel, S., Preuss, C. T., Sjöstrand, T., Skands, P., Utheim, M., & Verheyen, R.]

Sherpa 2: Begun in 2000. Originated in "matching" of matrix elements to showers: CKKW. Last version **Sherpa 2.2**: [Bothmann, E., Chahal, G. S., Höche, S., Krause, J., Krauss, F., Kuttimalai, S., Liebschner, S., Napoletano, D., Schönherr, M., Schulz, H., Schumann, S., & Siegert, F. (2019) SciPostPhys.7.3.034]

2. LHC MC

General purpose MC the Workhorses of the LHC:

How big was the progress?

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2. LHC MC

General purpose MC the Workhorses of the LHC:

How big was the progress?

C++

Herwig 7: Successor to EARWIG (begun in 1984). Originated in coherence studies: angular ordering parton shower. Cluster model. Last version: **Herwig 7.2** [Bellm, Bewick, Ravasio, Gieseke, Grellscheid, Kirchgaesser, Masouminia. Nail, Papaefstathiou, Platzer, Rauch, Reuschle, Richardson, Seymour, **Siodmok**, Webster, *Eur.Phys.J.C* 80 (2020)]

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2. LHC MC

	Current release series	Hard matrix elements	Shower algorithms	NLO Matching	Multijet merging	MPI	Hadronization	Shower variations
H7	Herwig 7	Internal, libraries, event files	QTilde, Dipoles	Internally automated	Internally automated	Eikonal	Clusters, (Strings)	Yes
	Pythia 8	Internal, event files	Pt ordered, DIRE,VINCIA	External	Internal, ME via event files	Interleaved	Strings	Yes
	Sherpa 2	Internal, libraries	CSShower, DIRE	Internally automated	Internally automated	Eikonal	Clusters, Strings	Yes

[Table from S. Platzer]

- NLO revolution - automated Matrix Element/Loop providers: Madgraph, Openloops, GoSam and Recola, ... NNLO (see R. Poncelet talk)
- "LO" Parton Showers, NLO Parton Showers (see Z. Nagy talk)
- All have some versions of QED Showers. YFS also in H7 (decays) and Sherpa (the most developed EEX YFS in General Purpose MC- A. Price's talk).
- Features developed for hadronic collisions have been/will be ported to e+e−.

2. LHC MC

KrkNLO designed specifically to reduce the complexity **of NLO matching to Parton Showers**

KrkNLO method: proof of concept for Z and H boson production
[**Jadach**, Nail, Placzek, Sapeta, **AS**, Skrzypek **EPJC** 77 (2017) no.3, 164, **Eur.Phys.J.** C76 (2016) no.12, 649, **JHEP** 1510 (2015) 052]

Based on a new MC factorization scheme which is tailored for GPMC

- The method is extremely simple
- No negative weights
- Simple at NLO -> hope to for NNLO + NLO PS

More processes
(gamma gamma, ...)
automatization
see J. Whitehead talk

Universality

Higher precision

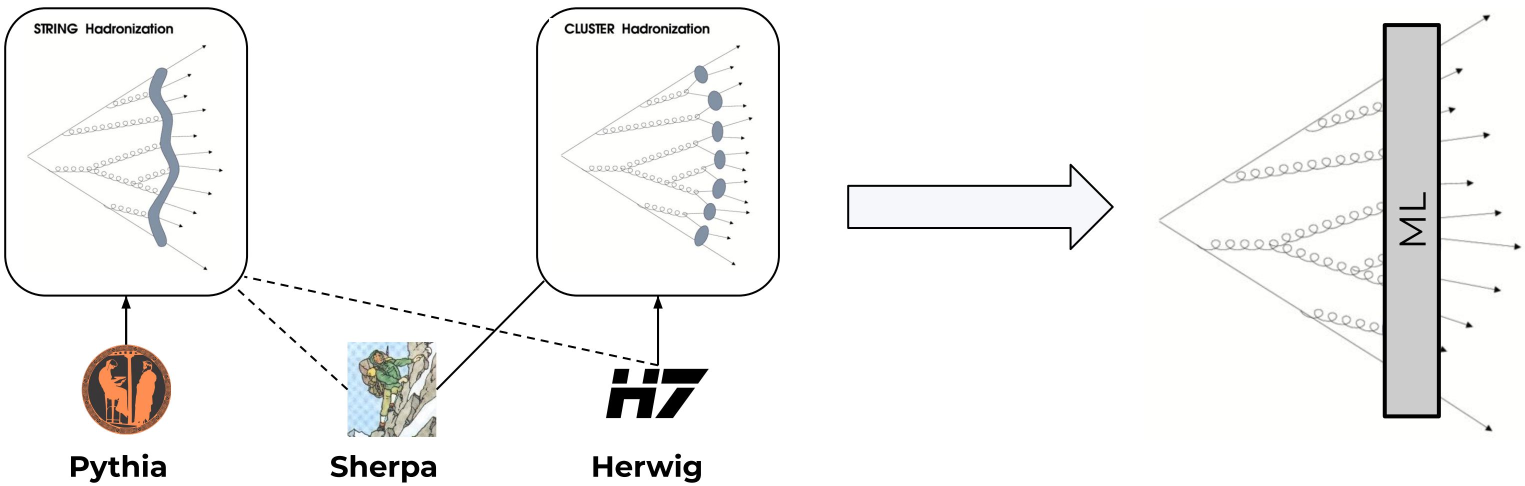
MC@NLO+KrkNLO
[Nason, Salam *JHEP* 01 (2022)]

2. LHC MC

Hadronization:

Early 1980's
(limited progress)

Early 2020's
(lot of progress in ML)



- ➔ Increased control of perturbative corrections ⇒ more often the precision of LHC measurements is limited by MCEG's non-perturbative components, such as hadronization.
- ➔ Hadronization (phenomenological models with many free parameters ~ 30 parameters)
- ➔ Hadronization is a fitting problem, ML is proved to be well suited for such a problems.

Idea of using Machine Learning (ML) for hadronization.

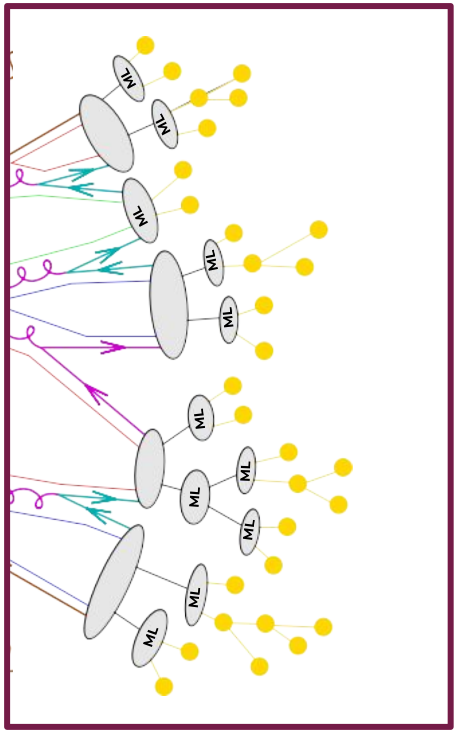
NNPDF used successfully ML to nonperturbative Parton Density Functions (PDF)

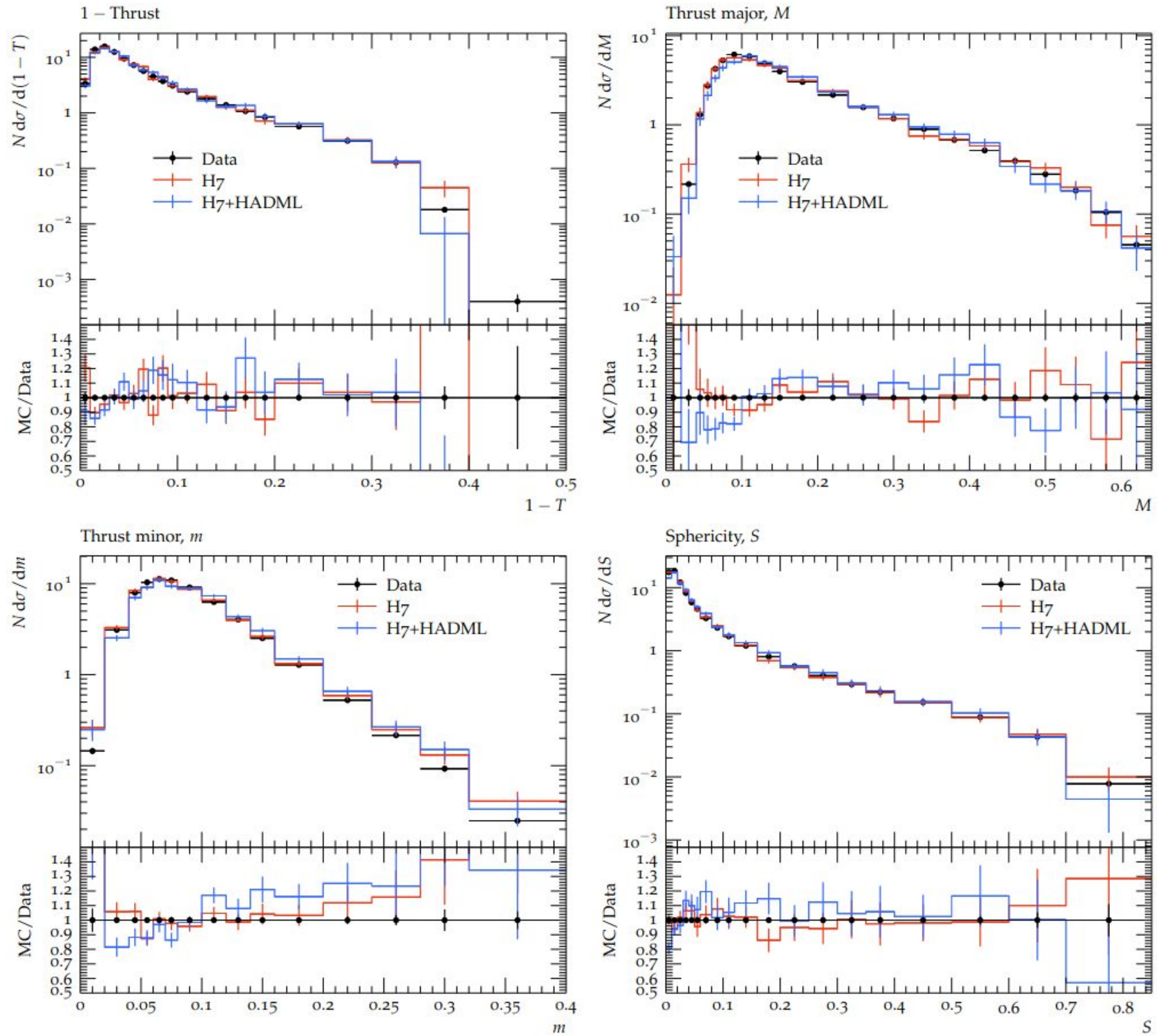
Results [Ghosh, Nachman, Siodmok, Yu, arXiv: 2203.12660]

Full-event Validation

(Full events using HADML integrated into Herwig 7)

LEP DELPHI **Data**





- The ultimate goal of is to train the ML model directly on data to improve hadronization models

Recent progress: Machine learning hadronization

First steps for ML hadronization:

- HADML - [A. Ghosh, Xi. Ju, B. Nachman **AS**, *Phys.Rev.D* 106 (2022) 9]
- MLhad - [P. Ilten, T. Menzo, A. Youssef and J. Zupan, SciPost Phys. 14, 027 (2023)]

	MLhad	HADML
Deep generative model:	Variational Autoencoder	Generative Adversarial Networks
Trained on:	String model	Cluster model
Recent progress:	*“Reweighting MC Predictions and Automated Fragmentation Variations in Pythia 8”* [Bierlich, Ilten, Menzo, Mrenna, Szewc, Wilkinson, Youssef, Zupan, 2308.13459] *“Towards a data-driven model of hadronization using normalizing flows”* [Bierlich, Ilten, Menzo, Mrenna, Szewc, Wilkinson, Zupan, 2311.09296]	*“Fitting a Deep Generative Hadronization Model”* [J. Chan, X. Ju, A. Kania, B. Nachman, V. Sangli and **AS,** JHEP 09 (2023) 084] “Integrating Particle Flavor into Deep Learning Models for Hadronization” [J. Chan, X. Ju, A. Kania, B. Nachman, V. Sangli and **AS,** 2312.08453]

2. LHC MC

Precise process-oriented MC
[main focus on QED/EW]

Precision Monte Carlos:
Theory predictions with <0.100% precision, so far only **KKMCee** and **BHLUMI** qualify, FCCee will require 0.001%.

KKMCee: $e^+e^- \to f\bar{f}(n\gamma),\ f = \mu, \tau, q, \tau \to X$

Rewritten to C++ [**Jadach**, Ward, Was, Yost, **AS**, CPC 2022]

- Resumed (exponentiated) multi photon effects at the AMPLITUDE level (CEEX scheme) keeping (exponentiated) initial-final state interferences.
- Non-soft complete QED complete up to 3-rd order LO, NLO 2-nd order, in the initial and final states,
- Complete (longitudinal and transverse) spin polarisation for the incoming beams and outgoing fermions (mandatory for tau pairs) including spin correlations.
- It is **intended to be a starting point for the future improvements**, which will be mandatory for the future high precision lepton collider projects.
- Validated against of Fortran version
- A number of improvements in the Monte Carlo algorithm

BHLUMI: did not change from LEP but it was used
[**Jadach** and Janot, Phys. Letters B803 (2020) 135319] LEP data reanalyzed:

$$N_\nu = 2.9840 \pm 0.0082 \ \to 2.9963 \pm 0.0074$$

[see P. Janot talk]

2. LHC MC

Specialized programs [see S. Banerjee talk]

Photos [N. Davidson, T. Przedzinski, Z. Was, CPC 199 (2016) 86-101]
[S. Antropov, Sw. Banerjee, Z. Was, J. Zaremba, 283 (2023) 108592]

- re-written to C++,
- emission of lepton pair was introduced,
- several processes, like Z,W,B meson decays emission kernels based on complete first order matrix element were introduced into fixed order and multiple photon mode of Photos operation.

Tauola [**S. Jadach**, Z. Was, R. Decker, J. H. Kuhn, CPC 76 (1993) 361-380], ...,
[M. Chrzaszcz, T. Przedzinski, Z. Was, J. Zaremba, CPC 232 (2018) 220-236]

- Multiple new tau decay modes, of new physics and of Standard Model were introduced into tauola.
- New version is now installed in Belle 2 software.
- Hopefully, new parametrization of hadronic currents for tau decay channels will become available to broader community in the forthcoming years.

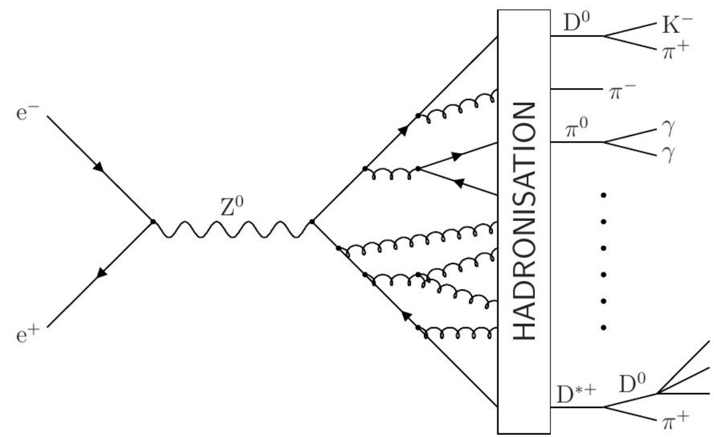
See: ECFA Higgs Factories: 1st Topical Meeting on Generators

3. Future-ee

General purpose MC QCD developments

- Better Parton Shower
  - NNLO + NLO Parton Shower?
  - Amplitude evolution?
  - Quantum Computers

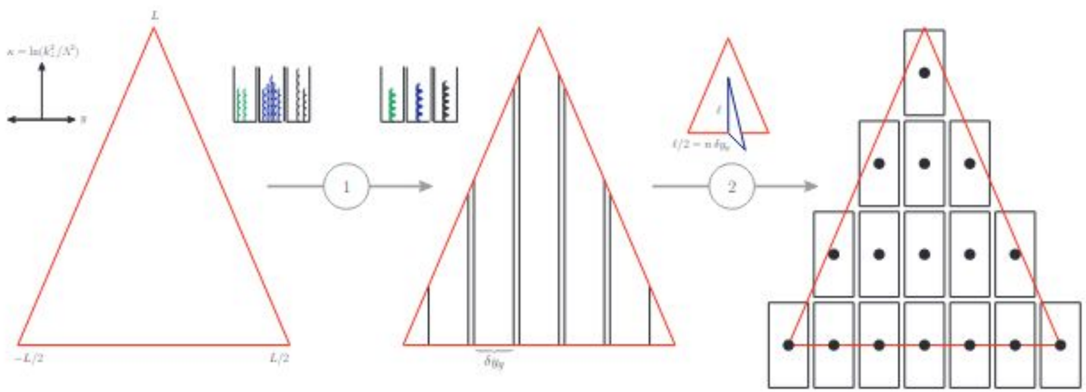
- Better Hadronization
  - lattice QCD?
  - ML?
  - improved string and cluster
  - new measurements



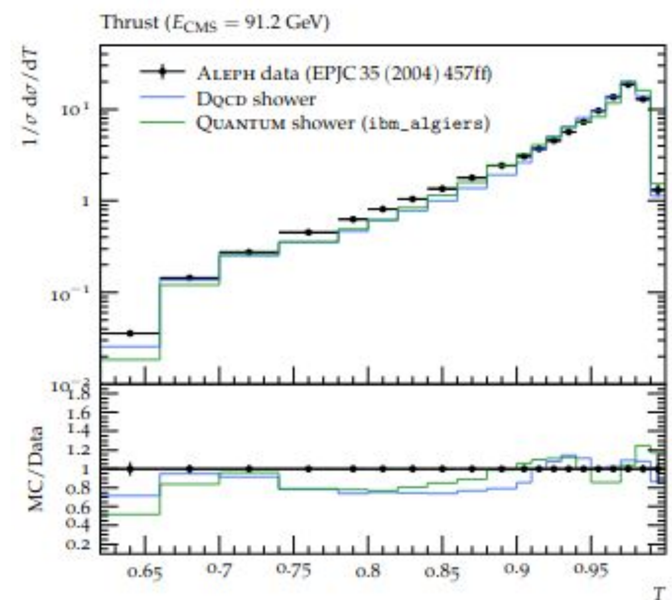
3. Future-ee

Collider Events on a Quantum Computer

Gösta Gustafson,[a] Stefan Prestel,[a] Michael Spannowsky,[b] Simon Williams[c]



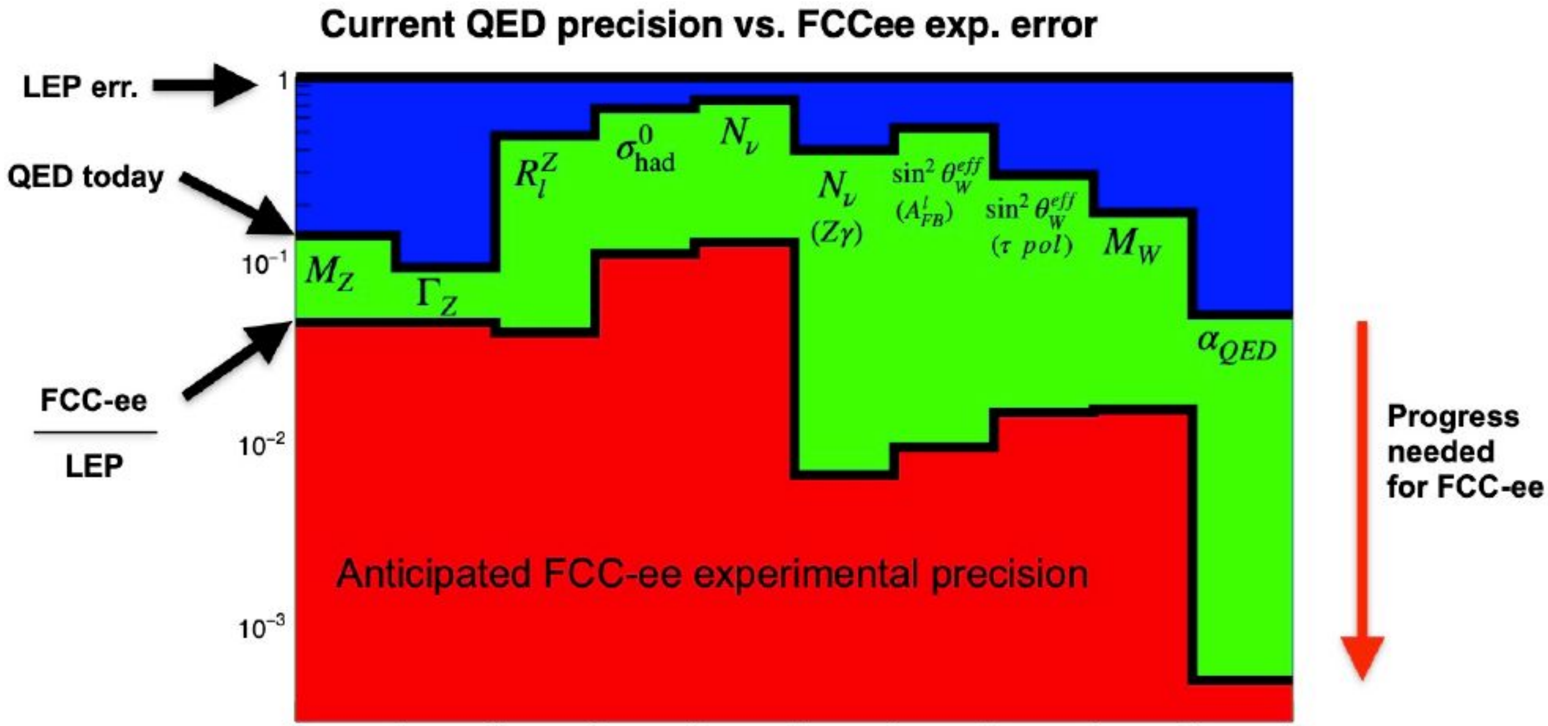
Simplified parton showers using the Discrete QCD method



"This is the first time a Noisy Intermediate-Scale Quantum (NISQ) device has been used to simulate realistic high-energy particle collision events" [2022]

3. Future-ee

Future e+e- machine will be precision factory (luminosity up to 10^5 higher then LEP)



Most sensitive to QED radiation observables
[Jadach, Skrzypek arXiv:1903.09895]

- The present precision of QED theoretical predictions would severely limit the analysis of precise measurements at FCC-ee.
- To properly confront the data with theoretical predictions of similar accuracy demands a huge progress in precision MC calculations!
- Needed factor 6-200 improvement with respect to LEP.

Example: KKMCee **[slide from S. Jadach talk at Epiphany 2021]**

Using the notation of [1303], the CEEX total cross section for the fermion pair production process at an electron collider, $\mathrm{e}^-(p_a)+\mathrm{e}^+(p_b)\to \mathrm{f}(p_c)+\bar{\mathrm{f}}(p_d)+\gamma(k_1),\dots,\gamma(k_n)$ reads as follows

$$\sigma^{(r)} = \sum_{n=0}^{\infty}\frac{1}{n!}\int d\tau_n(p_1+p_2;\ p_3,p_4,\ k_1,\dots,k_n)$$
$$\times\, e^{2\alpha\Re B_4(p_a,\dots,p_d)}\frac{1}{4}\sum_{\text{spin}}\left|\mathfrak{M}_n^{(r)}(p,k_1,k_2,\dots k_n)\right|^2,$$

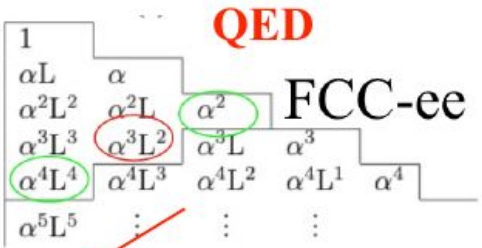
CEEX QED+EW matrix element in CEEX

where $\mathfrak{M}_n^{(r)}$ are the CEEX spin amplitudes, $d\tau_n$ is the standard LIPS, the virtual form factor B_4 is factorized (exponentiated) and the real emission spin independent soft factors $\mathfrak{s}$ are also factorized out. The momenta $p_1,\dots$ of the fermions are denoted collectively as p. The spin amplitudes read

Now in KKMC/CEEX ⟵

$$\mathfrak{M}_n^{(r)}(p,k_1,k_2,k_3,\dots,k_n) = \prod_{s=1}^{n}\mathfrak{s}(k_s)\Big\{\hat\beta_0^{(r)}(p) + \sum_{j=1}^{n}\frac{\hat\beta_1^{(r)}(p,k_j)}{\mathfrak{s}(k_j)} + \sum_{j_1<j_2}\frac{\hat\beta_2^{(r)}(p,k_{j_1},k_{j_2})}{\mathfrak{s}(k_{j_1})\mathfrak{s}(k_{j_2})}$$
$$+\sum_{j_1<j_2<j_3}\frac{\hat\beta_3^{(r)}(k_{j_1},k_{j_2},k_{j_3})}{\mathfrak{s}(k_{j_1})\mathfrak{s}(k_{j_2})\mathfrak{s}(k_{j_3})} + \sum_{j_1<j_2<\dots<j_r}\frac{\hat\beta_r^{(r)}(k_{j_1},k_{j_2},\dots,k_{j_r})}{\mathfrak{s}(k_{j_1})\mathfrak{s}(k_{j_2})\dots\mathfrak{s}(k_{j_r})}+\cdots\Big\}, \qquad (26)$$

$\mathcal{O}(\alpha^3)$ ⟵ $\mathcal{O}(\alpha^r)$



To be added for FCCee

$\mathcal{O}(\alpha^2)$ 2-loop **EW**

$\mathcal{O}(\alpha^2)$ 1-loop **EW**

such that the subtracted amplitudes $\hat\beta_j^{(r)}$ are IR-finite. In the $\mathcal{O}(\alpha^2)$ $(r=2)$ implementation of KKMC we define

$$\hat\beta_0^{(2)}(p) = \mathfrak{M}_0^{(2)}(p) = \left[e^{-\alpha B_4(p)}\mathcal{M}_0^{(2)}(p)\right]\Big|_{\mathcal{O}(\alpha^2)}, \qquad (27)$$

which includes QED and EW virtual corrections. In the future implementation of the $\mathcal{O}(\alpha^2)$ EW corrections, they would also enter into to the $2\to3$ non-soft components:

$$\hat\beta_1^{(2)}(p,k_1) = \mathfrak{M}_1^{(2)}(p,k_1) - \hat\beta_0^{(1)}(p)\mathfrak{s}(p,k_1),\quad \mathfrak{M}_1^{(2)}(p,k_1) = e^{-\alpha B_4(p)}\mathcal{M}_1^{(2)}(p,k_1)\Big|_{\mathcal{O}(\alpha^2)}. \qquad (28)$$

Watch out! The existing EW $\mathcal{O}(\alpha^2)$ calculations for $e^+e^-\to f\bar{f}$ are only for *inclusive* quantities.

3. Future-ee

https://github.com/KrakowHEPSoft/KKMCee

github.com/KrakowHEPSoft/KKMCee-dev

README

The KKMCee 5 Monte Carlo Generator version in C++

[The main authors: S. Jadach, B. F. L. Ward, Z. Was, S. A. Yost and A. Siodmok]

KKMCee 5 is a multi-photon Monte Carlo event generator KKMCee for lepton and quark pair production in lepton colliders.

This is a web page of KKMCee 5 Monte Carlo event generator [1] for lepton and quark pair production for the high energy electron-positron annihilation process. It is still the most sophisticated event generator for such processes. Its entire source code is rewritten in the modern C++ language. It reproduces all features of the older KKMCee code in Fortran 77 [2]. However, a number of improvements in the Monte Carlo algorithm are also implemented. Most importantly, it is intended to be a starting point for future improvements (for example described in 2303.14260), which will be mandatory for future high-precision lepton collider projects.

Download and Installation

The current version is KKMCee 5.02 which can be downloaded from: https://github.com/KrakowHEPSoft/KKMCee/releases

For installation, we recommend following the HowToStart file.

Contact

Any questions or comments can be directed to kkmc@uj.edu.pl

The main references to the KKMCee are listed below

[1] S. Jadach, B. F. L. Ward, Z. Was, S. A. Yost and A. Siodmok, “Multi-photon Monte Carlo event generator KKMCee for lepton and quark pair production in lepton colliders”, Comput. Phys. Commun. 283 (2023) 108556, [2204.11949].

[2] S. Jadach, B. F. L. Ward and Z. Was, “The Precision Monte Carlo event generator KK for two fermion final states in e+e− collisions”, Comput. Phys. Commun. 130 (2000) 260.

Contact:
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Conclusions

1. Apology for not covering all MC and their details ...
2. The progress in both General Purpose MC and precision MC will be needed for e+e- factory.
3. Will we be in better position then at LEP?
   Not necessary MC generators are complex and in 30 years we might lost the know how...
4. General Purpose MC: more precise perturbative QCD NNLO + NLO Parton Showers and Hadronization
5. Upgrade of LEP legacy MCs is good but limited strategy.
   For factor 50-150 improvement in precision one needs new innovative projects.
6. Future:
   - continuous dialogue with experimental community
   - more powerful computational techniques (ML) and computers (Quantum Computers)
   - new ideas (amplitude level Parton Showers, ML hadronization...)
7. One should avoid “monopoly” of a single MC for a given process/observable. The best would be (at least) two MCs of similar high quality developed independently by two or more groups of authors. [examples: YFSWW3 + RACOONWW, Herwig, Pythia, Sherpa]
8. Long way to go... fortunately since we don’t have DeLorean we have time...

Backup slides

KrkNLO - basic idea

Lets consider

DY cross section at NLO in collinear $\overline{\text{MS}}$ factorization for the $q\bar{q}$ channel:

$$\sigma^1_{\text{DY}} - \sigma^B_{\text{DY}} \quad = \quad \sigma^B_{\text{DY}}\, D_1^{\overline{\text{MS}}}(x_1,\mu^2) \otimes \frac{\alpha_s}{2\pi} C_q^{\overline{\text{MS}}}(z) \otimes D_2^{\overline{\text{MS}}}(x_2,\mu^2)\,,$$

where

$$C_q^{\overline{\text{MS}}}(z) = C_F \left[4\,(1+z^2)\left(\frac{\ln(1-z)}{1-z}\right)_+ - 2\frac{1+z^2}{1-z}\ln z + \delta(1-z)\left(\frac{2}{3}\pi^2 - 8\right)\right].$$

All solutions for NLO + PS matching which use $\overline{\text{MS}}$ PDFs, need to implement collinear remnant term of the type $4\,(1+z^2)\left(\frac{\ln(1-z)}{1-z}\right)_+$ that are technical artefacts of $\overline{\text{MS}}$ scheme.

The implementation is not easy since those terms correspond to the collinear limit but Monte Carlo lives in 4 dimensions and not in the phase space restricted by $\delta(k_T^2)$.
The idea behind the MC scheme is to absorb those terms to PDF.

KrkNLO - the method

1. Take a parton shower that covers the (α, β) phase space completely (no gaps, no overlaps) and produces emissions according to approx. real matrix element K.
2. Upgrade the real emissions to exact ME R by reweighting the PS events by $W_R = R/K$.
3. We define the coefficion function $C^R(z) = \int(R - K)$. To avoid unphysical artifacts of $\overline{\mathrm{MS}}$.
4. Transform PDF for $\overline{\mathrm{MS}}$ scheme to this new physical MC factorization scheme.
5. As a result the virtual+soft correction, Δ_{S+V}, is just a constant, without x-depended collinear remnant terms now. Multiply the whole result by $1 + \Delta_{S+V}$ to achieve complete NLO accuracy.

KrkNLO - example DY

- Our approach to NLO+PS matching (example: Drell-Yan)

Real part:

$$W_R^{q\bar{q}}(\alpha,\beta) = 1 - \frac{2\alpha\beta}{1+(1-\alpha-\beta)^2}$$

$$W_R^{qg}(\alpha,\beta) = 1 + \frac{\alpha(2-\alpha-2\beta)}{1+2(1-\alpha-\beta)(\alpha+\beta)}$$

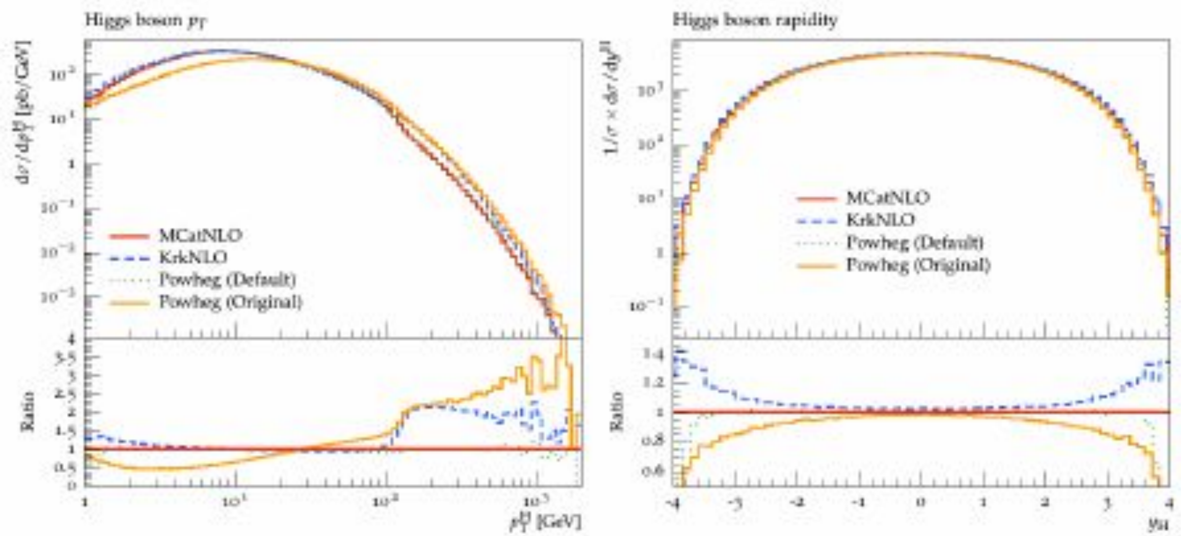
Virtual + soft:

$$W_{V+S}^{q\bar{q}} = \frac{\alpha_s}{2\pi} C_F \left[\frac{4}{3}\pi^2 - \frac{5}{2}\right]$$

$$W_{V+S}^{qg} = 0$$

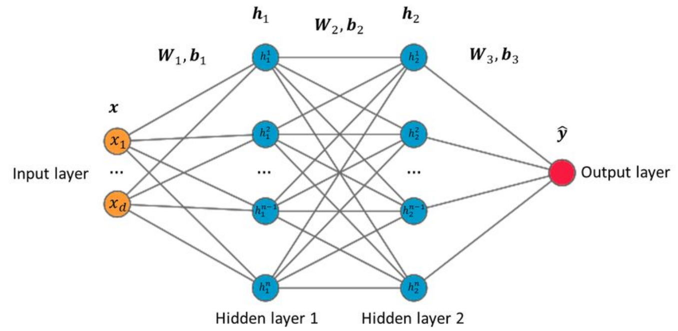
- PDF in MC factorization scheme - full definition

- KrkNLO for the Higgs boson production



Architecture: conditional GAN

(each a fully connected, hidden size 256, a batch normalization layer, LeakyReLU activation function)



Generator

Input

Cluster $(E,\ p_x,\ p_y,\ p_z)$ and 10 noise features sampled from a Gaussian distribution

Output (in the cluster frame)

ϕ - polar angle
θ - azimuthal angle

we reconstruct the four vectors of the two outgoing hadrons

Discriminator

Input

ϕ and θ labeled as signal (generated by Herwig) or background (generated by Generator)

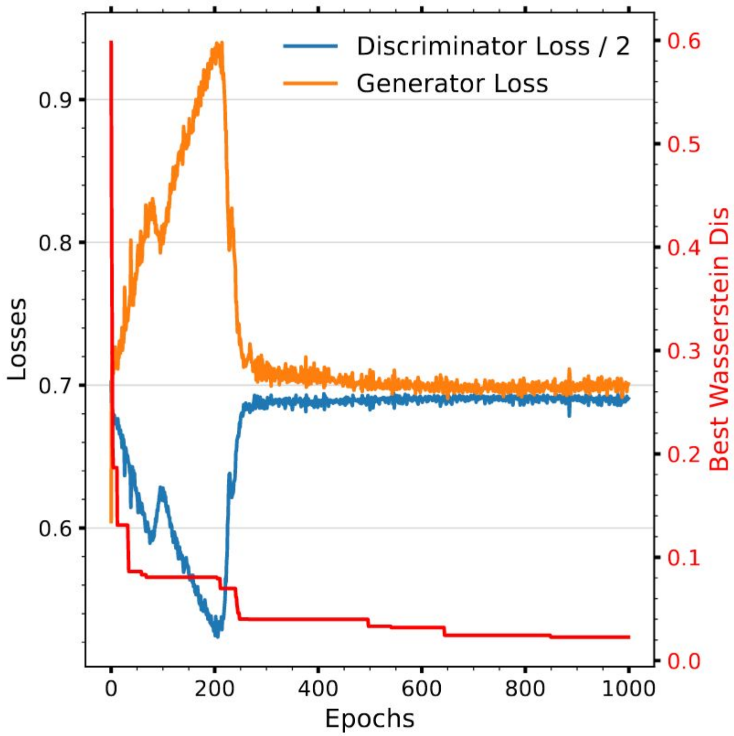
Output

Classification.

Training

cluster's four vector and angular variables are scaled to be between -1 and 1 (tanh activation function as the last layer of the Generator)

- **Discriminator** and the **Generator** are trained separately and alternately by two independent Adam optimizers with a learning rate of 10^{-4}, for 1000 epochs

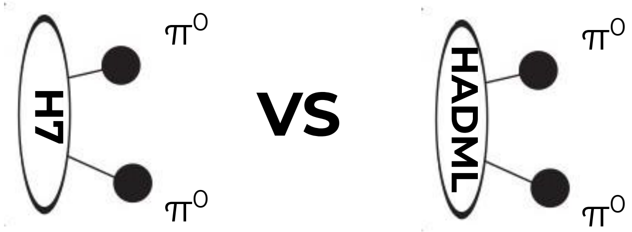


- **The best model** for events with partons of Pert = 0, is found at the epoch 849 with a total Wasserstein distance of 0.0228.

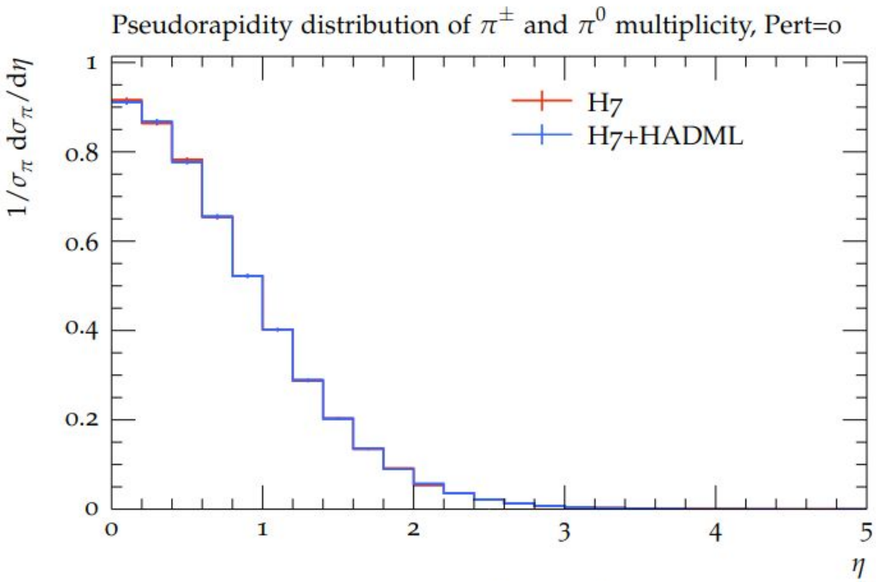
Results

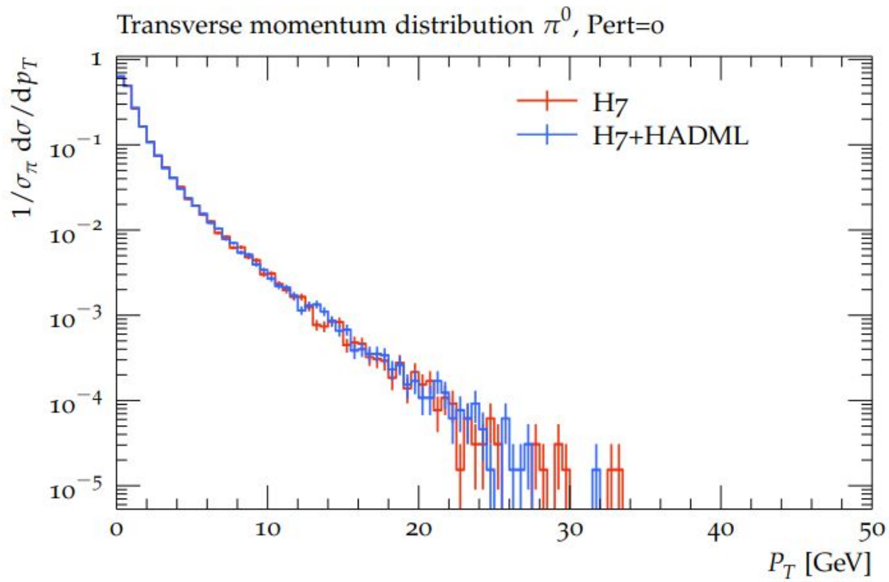
Low-level Validation
(similar to training data)

e^+e^- collisions at $\sqrt{s} = 91.2$ GeV



π^0 kinematic variables



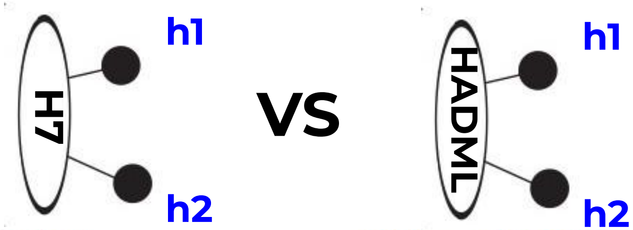


Pert = 0 (no memory of quark kinematics)

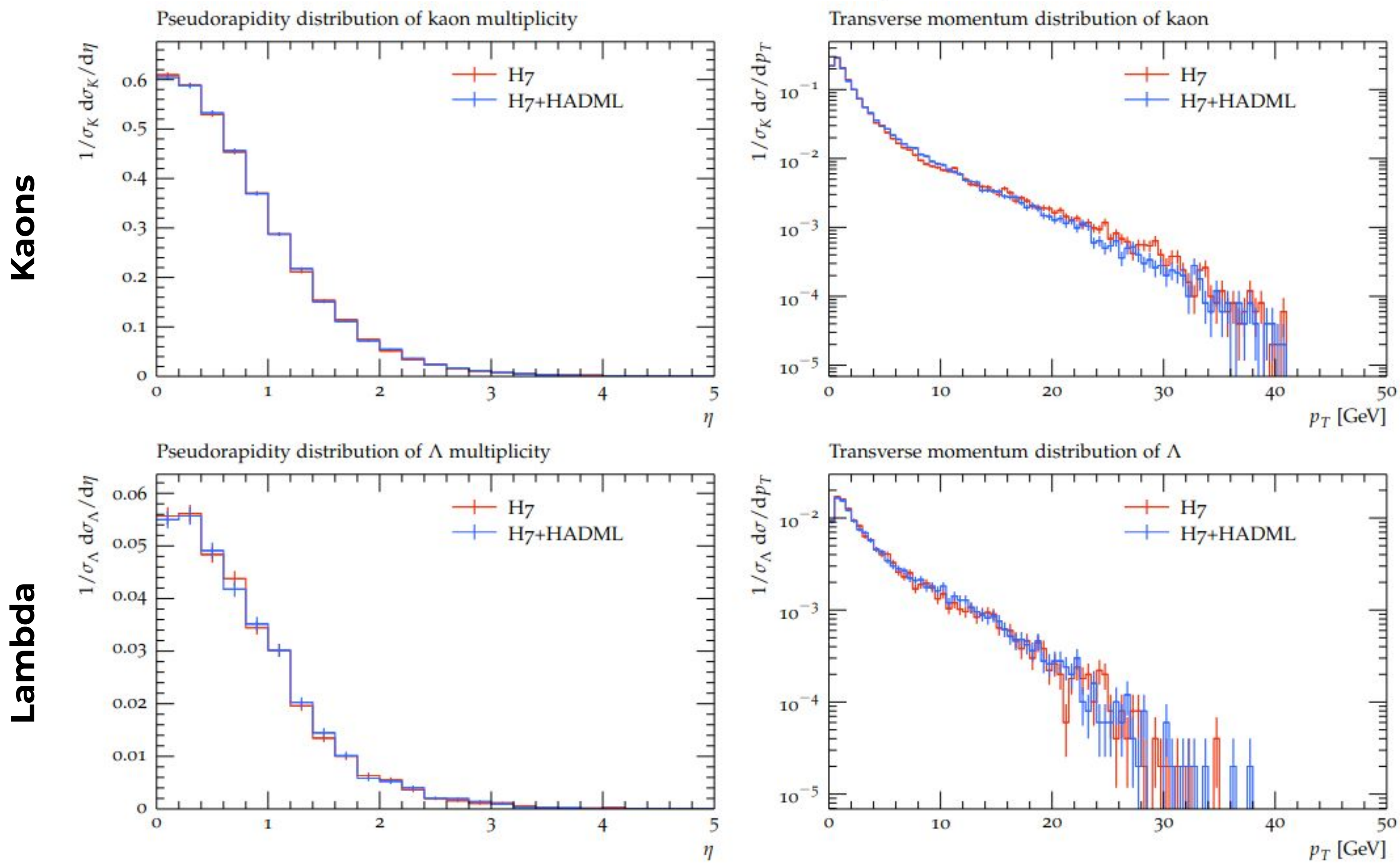
Results

Low-level Validation
(**beyond** training data **different hadrons**)

e^+e^- collisions at $\sqrt{s} = 91.2$ GeV



h kinematic variables



Minimax Loss

In the paper that introduced GANs, the generator tries to minimize the following function while the discriminator tries to maximize it:

$$E_x[log(D(x))] + E_z[log(1 - D(G(z)))]$$

In this function:

- `D(x)` is the discriminator's estimate of the probability that real data instance x is real.
- E_x is the expected value over all real data instances.
- `G(z)` is the generator's output when given noise z.
- `D(G(z))` is the discriminator's estimate of the probability that a fake instance is real.
- E_z is the expected value over all random inputs to the generator (in effect, the expected value over all generated fake instances G(z)).
- The formula derives from the cross-entropy between the real and generated distributions.

The generator can't directly affect the `log(D(x))` term in the function, so, for the generator, minimizing the loss is equivalent to minimizing `log(1 - D(G(z)))`.

Wasserstein distance

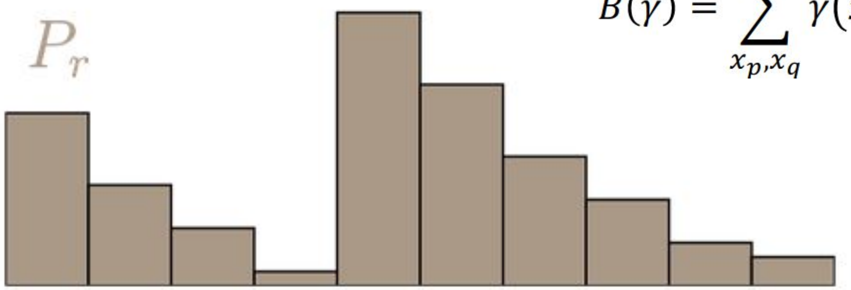
The Wasserstein distance

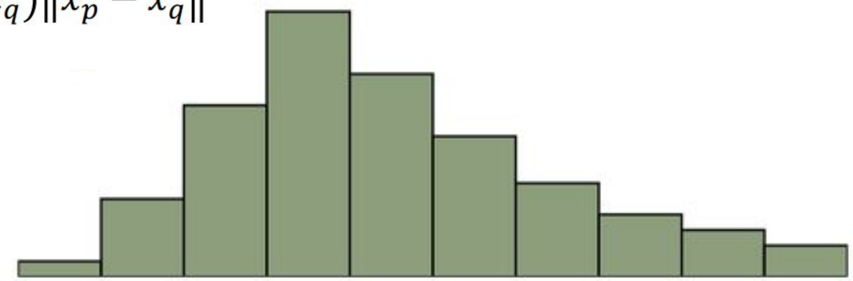
- For discrete probability distributions, the Wasserstein distance is called the earth mover’s distance (EMD):
- EMD is the minimal total amount of work it takes to transform one heap into the other.

$$W(P,Q) = \min_{\gamma \in \Pi} B(\gamma)$$

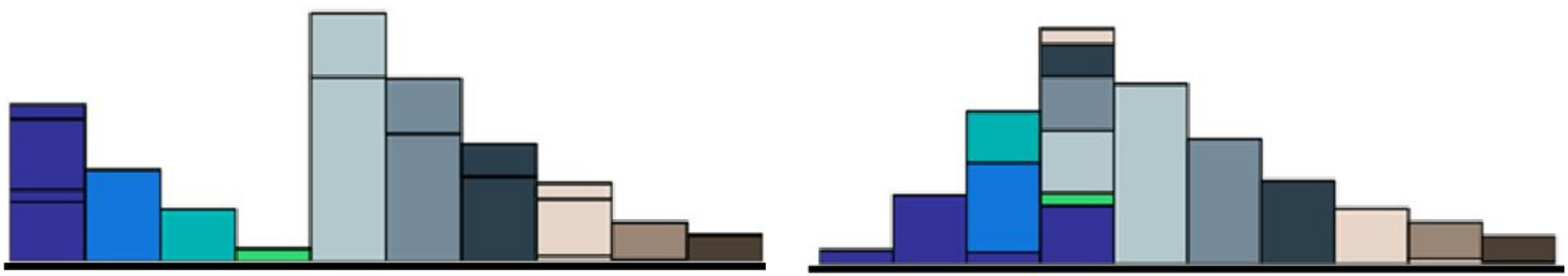
- Work is defined as the amount of earth in a chunk times the distance it was moved.

$$B(\gamma) = \sum_{x_p, x_q} \gamma(x_p, x_q) \|x_p - x_q\|$$

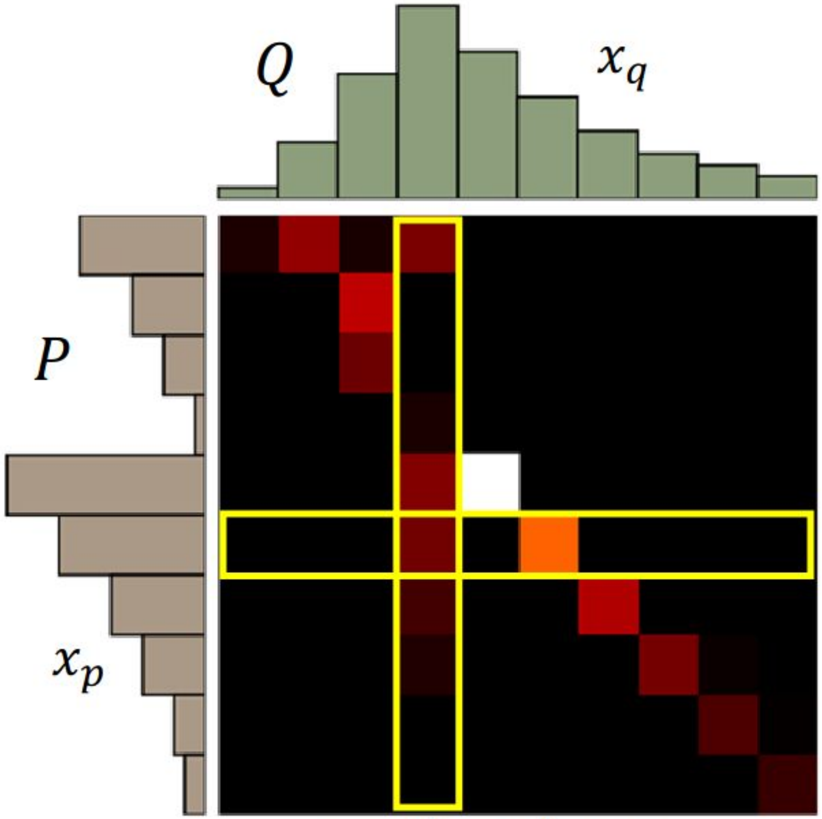




Best “moving plans” of this example



Wasserstein distance



moving plan γ
All possible plan Π

A "moving plan" is a matrix

The value of the element is the amount of earth from one position to another.

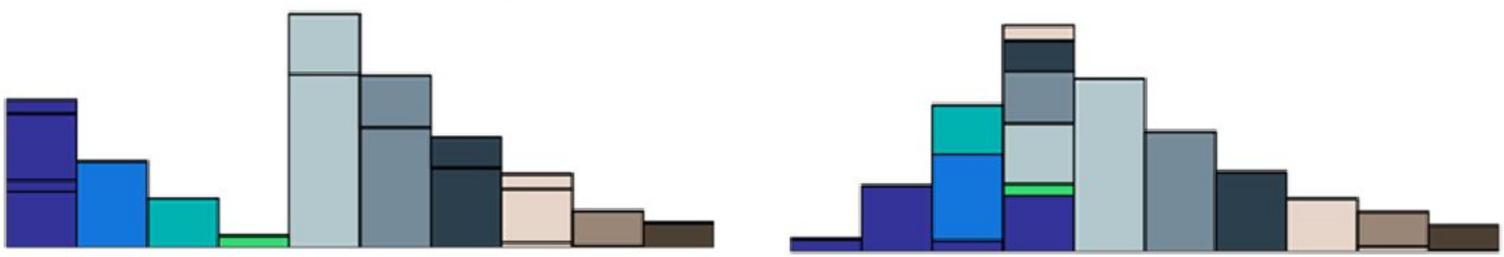
Average distance of a plan γ:

$$B(\gamma) = \sum_{x_p, x_q} \gamma(x_p, x_q) \|x_p - x_q\|$$

Earth Mover's Distance:

$$W(P, Q) = \min_{\gamma \in \Pi} B(\gamma)$$

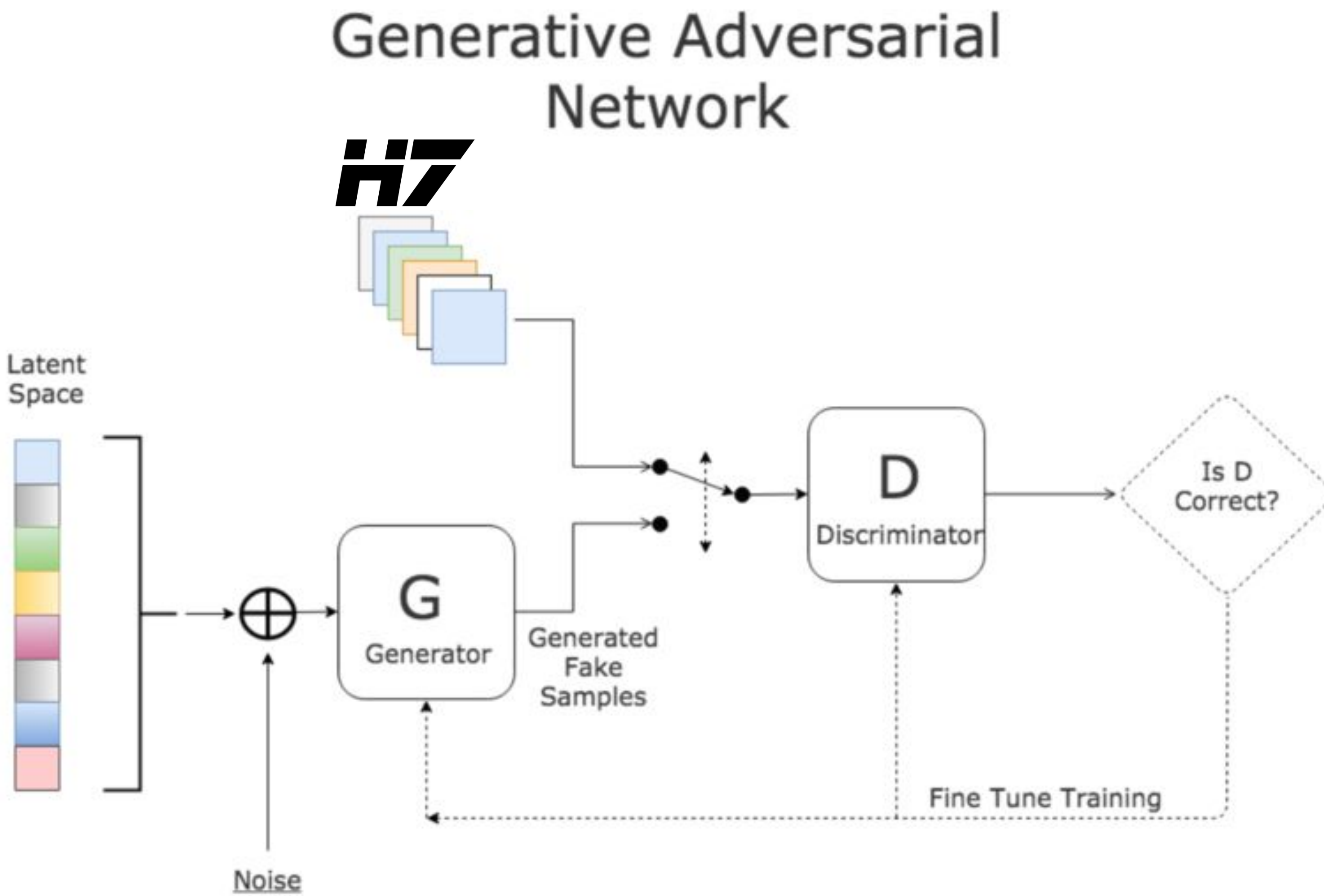
The best plan



2. LHC MC

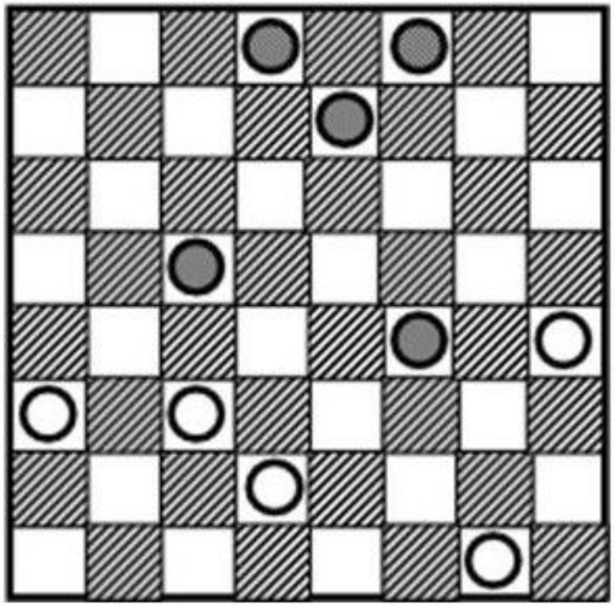
Towards a Deep Learning Model for Hadronization

[A. Ghosh, Xi. Ju, B. Nachman **AS**, *Phys.Rev.D* 106 (2022) 9]



Adversarial Networks

Arthur Lee Samuel (1959) wrote a program that learnt to play checkers well enough to beat him.



- He popularized the term **"machine learning"** in 1959.
- The program chose its move based on a **minimax** strategy, meaning it made the move assuming that the opponent was trying to optimize the value of the same function from its point of view.
- He also had it play thousands of **games against itself** as another way of learning.

Effectively the strength of the QED

$$\gamma_{nr} = \left(\frac{\alpha}{\pi}\right)^n \left(2\ln\frac{M_Z^2}{m_f^2}\right)^r, \; 0 \le r \le n,$$

(a) 0.6%

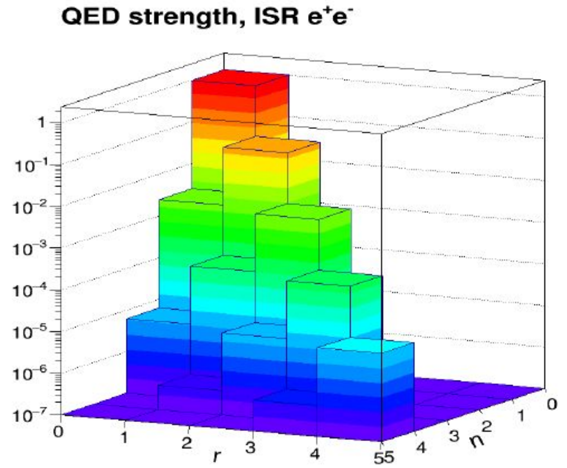
1				
αL	α			
$\alpha^2 L^2$	$\alpha^2 L$	α^2		
$\alpha^3 L^3$	$\alpha^3 L^2$	$\alpha^3 L$	α^3	
$\alpha^4 L^4$	$\alpha^4 L^3$	$\alpha^4 L^2$	$\alpha^4 L^1$	α^4
$\vdots$	$\vdots$	$\vdots$		

(b) 0.03%

1				
αL	α			
$\alpha^2 L^2$	$\alpha^2 L$	α^2		
$\alpha^3 L^3$	$\alpha^3 L^2$	$\alpha^3 L$	α^3	
$\alpha^4 L^4$	$\alpha^4 L^3$	$\alpha^4 L^2$	$\alpha^4 L^1$	α^4
$\vdots$	$\vdots$	$\vdots$		

(c) 0.001%

1				
αL	α			
$\alpha^2 L^2$	$\alpha^2 L$	α^2		
$\alpha^3 L^3$	$\alpha^3 L^2$	$\alpha^3 L$	α^3	
$\alpha^4 L^4$	$\alpha^4 L^3$	$\alpha^4 L^2$	$\alpha^4 L^1$	α^4
$\alpha^5 L^5$	$\vdots$	$\vdots$	$\vdots$	



- The (complete) order-by-order perturbative calculation in QED is definitely not the economic way to to obtain predictions for cross sections or asymmetries with the precision below 0.1%.
- Soft photon resummation is an absolute necessity, especially for resonant processes. It exists in at least three different variants (IEX, EEX and CEEX).
- Do not follow Bloch-Nordsieck to eliminate IR singularities!
- Resummation of collinear mass logarithms $\ln(s/m_f^2)$ is very useful, but in QED it is usually convenient to truncate it at some finite order.
- Approximation of small lepton mass $m_f^2/s \ll 1$ should be exploited for electron and muons as much as possible, but for τ lepton $\propto m_\tau^2/s, m_\tau^4/s^2$ terms may not be negligible at tree-level, while higher powers of this type in higher orders of α are probably irrelevant.